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# Bunching And Cooling Of Radioactive Ions With REXTRAP

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**Abstract.** The properties of radioactive ion beams produced by the present on-line target ion source technology are often not suitable for direct post acceleration. For that purpose pulsed and cooled beams of higher charged ions are required. In the case of REX-ISOLDE, the post accelerator at the CERN-ISOLDE radioactive beam facility, a unique system for beam preparation is used. It consists of a gas-filled cylindrical Penning trap (REXTRAP) for bunching and cooling followed by an electron beam ion source for charge state breeding. The Penning trap has been successfully operated with an efficiency of up to 40% and a total number of up to  $10^7$  ions stored. Buffer-gas sideband cooling at the ions' cyclotron frequency is employed for centering of the ions in the trap. Space charge effects have been observed if more than  $10^5$  ions are stored. The main effects are frequency shifts for the centering frequency. They can not be explained by simple single ion trap theory, but can be reproduced in simulations.

## INTRODUCTION

The aim of the REX-ISOLDE project [1] is to post-accelerate radioactive ions produced by the CERN ISOLDE facility up to an energy between 0.8 and 2.2 MeV/u. With this a new class of experiments studying nuclear structure physics, astrophysics and nuclear solid-state physics will become possible. Beams of radioactive ions are produced at ISOLDE by bombarding a target with high-energy protons, extracting and ionizing the reaction products and selecting the desired species by mass separation. The ions available have a typical energy of 60 keV, are singly charged and have a transversal beam emittance of about  $35 \pi \text{ mm mrad}$ . Beam currents are ranging from a few ions per second up to several nA depending on the target ion source combination and the desired nuclide. Efficient post-acceleration requires highly charged ions and a pulsed beam with low emittance. Thus, beam preparation is necessary. For REX-ISOLDE a unique system has been chosen, which consists of a long cylindrical gas filled Penning trap for ion accumulation, bunching and cooling, and an electron beam ion source (EBIS) for charge state breeding. Final acceleration is done by a conventional heavy ion linac.

In a buffer buffer-gas filled Penning trap the reduction of the transversal phase space volume can be achieved by a sideband cooling technique using an excitation of the motion of stored ions at their cyclotron frequency. This has been theoretically studied and described in Ref. [2-4] and proven experimentally in [5]. The technique is well understood if only few ions are trapped, i.e. when no space charge effects have to be taken into account. Until now, no analytical model for describing the sideband cooling technique at the cyclotron frequency together with space charge effects is available but numerical simulations can be done [6].

## THEORY

The theory of the motion of a particle inside a Penning trap has been described in many publications, see for example [4,7]. The potential inside a cylindrical electrode structure with appropriate symmetry and voltages applied can be approximated by

$$\Phi_T = \frac{m\omega_z^2}{2q} \left( z^2 - \frac{\rho^2}{2} \right) \quad (1)$$

where  $m$  and  $q$  are mass and charge of the trapped ion and  $\omega_z$  its axial oscillation frequency.  $z$  and  $\rho$  are coordinates in a cylindrical coordinate system with origin at the trap's center. With a superimposed homogenous magnetic field  $B$  in  $z$ -direction the equation of motion leads to three eigen motions of particles in the trap: one oscillation in longitudinal ( $z$ ) direction at the frequency  $\omega_z$  and two circular motions in the perpendicular plane, the magnetron motion ( $\omega_+$ ) and the reduced cyclotron motion ( $\omega_-$ ), with

$$\omega_+ + \omega_- = \omega_c, \quad (2)$$

where  $\omega_c = \frac{q}{m} B$  is the cyclotron frequency.

The influence of the buffer gas can be described as viscous force acting on the particle, which can be written as

$$\vec{F} = -\delta m \vec{v}. \quad (3)$$

$\delta$  can be taken from tabulated values for ion mobilities in gases [8]. Assuming this being only a small perturbation, the eigen frequencies will remain constant and only the amplitudes will undergo changes. In the case of the axial oscillation and the reduced cyclotron motion this leads to a reduction of the amplitude but for the magnetron motion the radius will increase. Thus, the particle motion becomes unstable.

An additional azimuthal quadrupolar electric field at the cyclotron frequency can be employed to couple the two radial motions. This leads to an exponential decrease of the amplitudes of both motions and results in a centering of the particles inside the trap. The corresponding time constants for the reduction of the radii are equal and for sufficient rf-amplitude they reach a minimum at

$$\alpha = -\frac{\delta}{2} . \quad (4)$$

For example, the damping constant for  $^{133}\text{Cs}$  ions in Ar buffer gas at a pressure of  $10^{-4}$  mbar is  $\alpha = 150 \text{ s}^{-1}$ . The final ion cloud size is determined by the collisions with the buffer gas and therefore by the temperature of the gas.

If a large number of particles are involved space charge will change the potential given in equation 1. But assuming an elliptically shaped charge distribution [9] the quadratic dependence of equation 1 will remain. Thus, the formalism for solving the equation of motion, especially equation 2, will remain valid.

## EXPERIMENT AND RESULTS

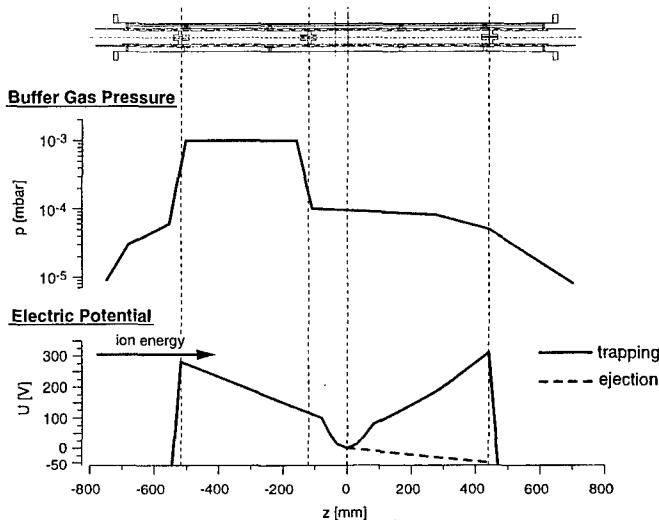


FIGURE 1. electrode structure, pressure and voltage distribution for REXTRAP.

The experimental set-up of REXTRAP is described in detail elsewhere [10]. In order to decelerate the ions in a first step the trap is placed on a high-voltage-platform near to 60 kV. Figure 1 shows the distribution of buffer gas pressure inside the trap as well as the potentials employed for accumulation and ejection of the ions. After passing the entrance potential hill of the trap the ions are finally stopped via collisions with the buffer gas atoms. They accumulate in the potential minimum at the trap center. A quadrupolar rf-field for the sideband cooling is applied to the fourfold segmented central trap electrode. After accumulation and cooling the potential hill at the trap exit is removed by switching down the potential at the corresponding electrodes, which releases the ions as a short bunch. The ions are accelerated again to ground potential, i.e. to 60 keV, and transported to the EBIS. For the sequence of accumulation and ejection a minimum cycle time of about 20 ms has been realized, which allow also short-lived isotopes to be handled.

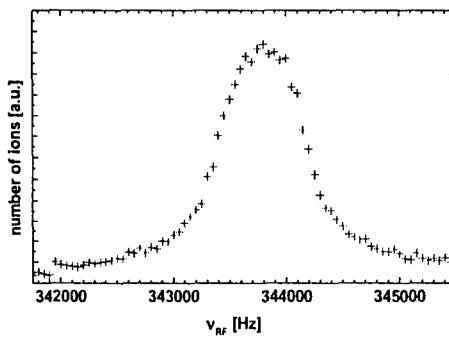


FIGURE 2. Number of ejected  $^{133}\text{Cs}$  ions as a function of the applied radio frequency

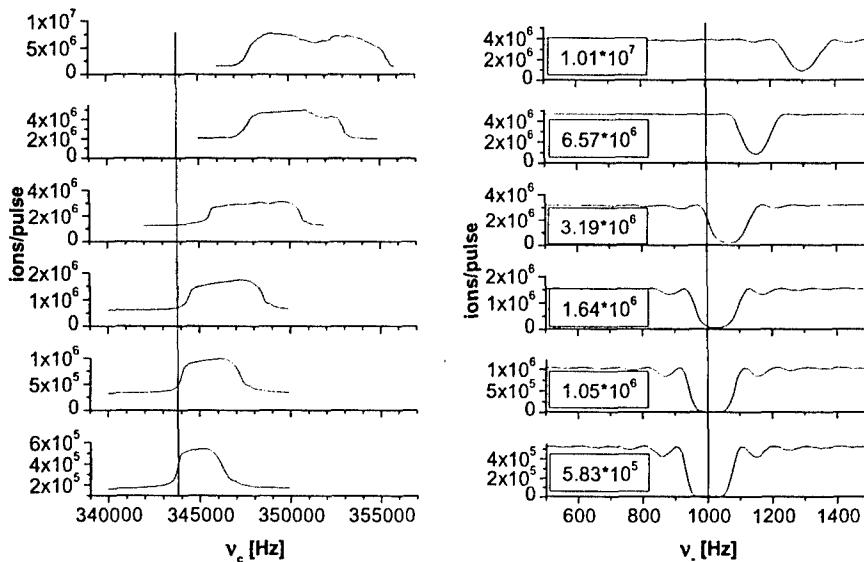


FIGURE 3. Number of ejected ions as a function of rf-frequencies for different number of stored ions. Left: signal as a function of the frequency of the quadrupolar rf-field for centering. Right: signal as function of the dipolar rf-field for driving the magnetron motion. The vertical lines represent the resonance frequencies for ion numbers below  $10^5$ .

Experiments have been performed with stable and radioactive ions ranging from  $^7\text{Li}$  up to  $^{181}\text{Ta}$  injected from a test ion source and from ISOLDE. As buffer gas the noble gases He, Ne and Ar have been used. A total efficiency of up to 40 % could be obtained. Since the exit diaphragm of the trap is smaller than the entrance one, successful cooling can be detected by an increase in the count rate of ejected ions. A typical cooling resonance for  $^{133}\text{Cs}$  with a total numbers of less than  $10^5$  simultaneously stored ions is shown in figure 2. If the number of stored ions is increased a significant broadening of the resonance lines and a shift of the center can be observed. For  $^{133}\text{Cs}$  this shift can be a few kHz, compared to the cyclotron frequency of about 345 kHz. The

effect can not be explained by the sum of the shifts of the magnetron or reduced cyclotron frequency.

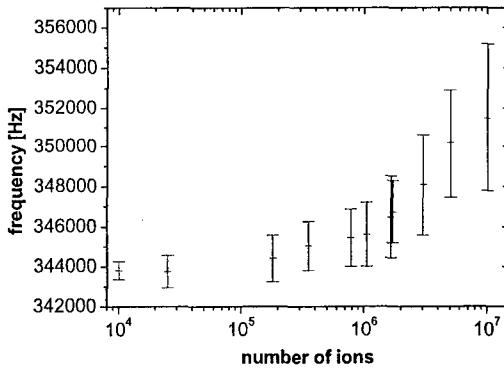


FIGURE 4 Centering frequency and width of centering resonances measured for  $^{133}\text{Cs}$  ions

These two frequencies can be measured by applying an azimuthal dipole rf-field after cooling. In resonance this excitation increases the amplitude of the motion again and results in a loss of the ions. As an example figure 3 (right) shows the resonance lines for the excitation near the magnetron frequency. It can be seen, that the magnitude of the shift is much smaller than for the applied centering frequency. A similar result, with a small downshift, could be obtained for the reduced cyclotron frequency. In figure 4 a summary of all measured spectra for the cooling of  $^{133}\text{Cs}$  is shown. In addition to the frequency shifts a decrease of the efficiency for ion ejection has been observed, indicating that even after centering the ion cloud's diameter becomes larger than the diameter of the exit diaphragm.

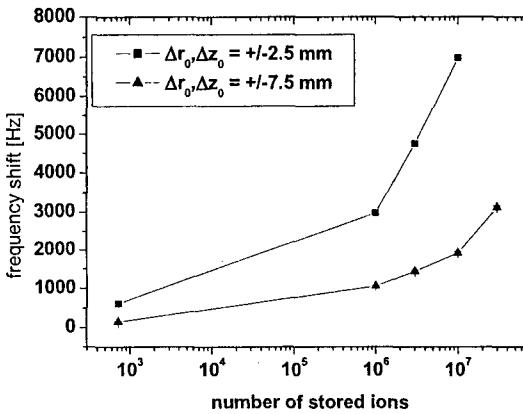


FIGURE 5 Calculated frequency shift for the centering of  $^{133}\text{Cs}$  ions as a function of the number of stored ions for different initial ion cloud sizes according to simulations

To further understand this behavior simulations of the ion motion and the cooling process have been carried out, in which space charge effects have been taking into ac-

count. To simulate the Coulomb interaction between the ions their electrical charge was scaled in such a way that only about 2000 ions represent the charge of  $10^7$  ions. Figure 5 shows the optimum centering frequency obtained in such a way for two different initial cloud sizes as a function of the number of stored ions. A very similar behavior to that depicted in figure 4 can be observed. The final ion cloud sizes after 20 ms of sideband cooling according to the simulations could be determined to be about 5 mm in diameter and 10 mm in length for  $10^7$  stored ions.

## SUMMARY

It has been demonstrated that a gas-filled Penning trap can be used for efficient accumulation and bunching of ions for ion beam preparation. For centering of the ions, i.e. a reduction of the transversal phase space, a sideband cooling technique at the cyclotron frequency has been used. Originally developed for the cooling of only a small number of ions this method has been extended to up to  $10^7$  stored ions. Space charge effects mainly cause an upward shift in the sideband cooling resonance. This behavior can not be understood easily by single ion theory, but it can be reproduced qualitatively by simulations. The strong dependence of the frequency on the initial size of the ion cloud indicates that the ion density is an important parameter.

For the accumulation and cooling of radioactive ions this is not a major drawback as in most cases only a small number of ions are delivered from the mass separator. However, in some cases isobaric contaminations can be higher. Here the adaptation of the applied frequency to the actual ion density can improve the cooling. First experiments could demonstrate an increase in the ion signal by a two-step increase in the frequency. To find an optimal excitation scheme for such cases further investigations will be done.

## ACKNOWLEDGMENTS

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